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ARTICLE

Spatiotemporal model for assessing the stability of urban human convergence and divergence patterns

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ABSTRACT

Understanding the stability of urban flows is critical for urban transportation, urban planning and public health. However, few studies have measured the stability of aggregate human convergence or divergence patterns. We propose a spatiotemporal model for assessing the stability of human convergence and divergence patterns. A mobile phone location data set obtained from Shenzhen, China, was used to assess the stability of daily human convergence and divergence patterns at three different spatial scales, i.e. points (cell phone towers), lines (bus lines) and areas (traffic analysis zones [TAZs]). Our analysis results demonstrated that the proposed model can identify points and bus lines with time-dependent variations in stability, which is useful for delineating TAZs for transportation planning, or adjusting bus timetables and routes to meet the needs of bus riders. Comparisons of the results obtained from the proposed model and the widely used entropy measure indicated that the proposed model is suitable for assessing the differences in stability for various types of spatial analysis units, e.g. cell phone towers. Therefore, the proposed model is a useful alternative approach of measuring spatiotemporal stability of aggregate human convergence and divergence patterns, which can be derived from the space–time trajectories of moving objects.

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Convergence; divergence; human mobility; stability; mobile phone data

1. Introduction

Understanding human mobility patterns can provide insights into the driving forces that affect human movements as well as the interactions between humans and the functional configuration of urban environment, thereby providing benefits in various fields such as urban transportation (Wang \textit{et al.} 2012), urban planning (Ratti \textit{et al.} 2006), urban policy development and public health (Mao \textit{et al.} 2016). Previous studies have mainly analyzed human mobility patterns to understand these driving forces and interactions from either the individual or aggregate perspective. Many studies have analyzed the spatiotemporal mobility behavior of individuals (Ratti \textit{et al.} 2006, Yuan and Raubal 2012, Liu \textit{et al.} 2015) and their activities (e.g. work, shopping or entertainment).
Phithakkitnukoon et al. 2010) in order to predict reproducible patterns (Gonzalez et al. 2008, Simini et al. 2012), including residential mobility and daily-to-weekly mobility (Sevtsuk and Ratti 2010). Aggregate human mobility patterns have been investigated using various approaches, such as identifying ‘sink’ and ‘source’ areas (Liu et al. 2012) or hot spot areas (Hoteit et al. 2014, Hu et al. 2014, Lichman and Smyth 2014, Scholz and Lu 2014), investigating human convergence and divergence patterns (Yang et al. 2016), and identifying activity groups (Shen and Cheng 2016) or mobility clusters (Hammond and Thompson 2002). Studies of individual and aggregate human mobility can elucidate the nature of mobility at various spatial and temporal scales, but the stability of human mobility has not received sufficient attention in previous investigations.

Human convergence and divergence patterns are important and common manifestations of aggregate human mobility patterns in urban space, and their stability is critical for understanding the forces that drive human movement as well as the efficiency of the interactions between humans and the functional configuration in order to facilitate urban policy development. Several studies have focused on the stability of individuals in cities (Hanson 2005) and the temporal stability (Hammond and Thompson 2002) of walking trips (Mittra et al. 2010), as well as the space–time structure of human mobility (Sun et al. 2011). However, it is still necessary to measure the stability of aggregate human mobility (i.e. convergence or divergence). In this study, we propose an approach for measuring the stability of aggregate human convergence and divergence to address this deficiency.

The research question addressed in this study is how to model the stability of human convergence and divergence using mobile phone big data. The appearance of convergence or divergence in an urban space unit comprises a sequence, which is not immutable and changes over time. The stability of this sequence may indicate changes in the travel demand for a place. Quantitative analyses based on the stability of this sequence can provide insights into the fluctuations in travel demand in an urban space, thereby yielding valuable information for traffic managers and urban planners when designing policies, such as planning bus lines and operating times. Several approaches have been used to investigate human mobility, such as questionnaires, travel diaries and geo-referenced human movement data sets obtained from different types of location-aware devices (e.g. mobile phones, smart cards and GPS-enabled taxis) (Lu and Liu 2012, Shaw et al. 2016). However, it is difficult to use questionnaires or travel diaries to investigate human convergence and divergence because they contain coarse space–time information and their sample sizes are limited (Ratti et al. 2006, Yuan and Rauhal 2012). By contrast, geo-referenced human movement big data provide new opportunities for understanding human convergence and divergence patterns on unprecedented spatial and temporal scales (Xu et al. 2015). Thus, we used mobile phone location data to investigate the stability of human convergence and divergence patterns because of the advantages of these data for capturing human mobility in the urban environment.

Our study makes the following three main contributions. First, we propose a model for characterizing the stability of human divergence or divergence processes and sequences. Second, we demonstrate the feasibility of our model for assessing the stability of human convergence and divergence in three types of space units, i.e. locations, traffic analysis zones (TAZs) and bus transit lines, thereby providing a reference for optimizing and rescheduling bus line timetables and routes in order to
improve the efficiency of public transport systems. Third, we compare the different capabilities of our model and the widely used entropy method for measuring the stability of human convergence and divergence.

The remainder of this paper is organized as follows. Section 2 reviews previous studies of aggregate human mobility based on big data and stability measurements. In Section 3, we propose an assessment model for characterizing the stability of human convergence or divergence processes and sequences. In Section 4, we present the study data set and analyses of the results obtained for three types of space units. The different capabilities of our model and the entropy method are compared and analyzed in Section 5. We give our conclusions in Section 6.

2. Related work

In this section, we review related research into aggregate human mobility using big data and stability measurements.

Three groups of approaches have been used to investigate aggregate human mobility. The first group aims to detect human mobility or activity hotspots to determine the mobility demand or activities in different places. Thus, Hotteit et al. (2014) detected human mobility hotspots based on human trajectories; Scholz and Lu (2014) defined a six-stage life cycle to model the dynamics of activity hot spots; and Hu et al. (2014) and Lichman and Smyth (2014) used kernel density estimation to generate a human mobility smooth surface based on the point locations obtained from moving objects. Liu et al. (2012) borrowed the ‘source area and sink area’ concept from ecology to characterize daily travel patterns, where they classified study areas into six traffic source-sink areas based on the temporal vectors of taxi pick-ups and drop-offs. Zhu and Guo (2014) proposed a hierarchical clustering method for mapping large spatial flow data (taxi trips), which can generalize origin–destination flows to represent the main human inflow and outflow areas.

The second group of approaches aims to identify concentrated human activity areas such as human activity groups, regions of interest, semantically similar areas and spatially interacting communities. For example, Schneider et al. (2013) found 17 unique networks of mobility motifs that captured up to 90% of the population based on surveys and mobile data sets for different countries. Pappalardo et al. (2015) identified the existence of two distinct classes of individuals, i.e. returners and explorers, and showed that their mobility patterns and social interactions were correlated. Hu et al. (2015) extracted urban areas of interest using geotagged photos. Shen and Cheng (2016) modeled activities as visits to spatiotemporal regions of interest and proposed a framework for identifying activity groups based on space–time profiles. Steiger et al. (2016) proposed a geographic, hierarchical self-organizing map to explore spatiotemporal and semantic clusters in Twitter data. In addition, Sobolevsky et al. (2013) delineated geographical regions using networks of human interactions, while Gao et al. (2013) discovered spatially interacting communities based on mobile phone data. All of these methods are helpful for understanding active areas of interest for urban planning.

The third group of approaches aims to investigate the spatiotemporal dynamics or rhythms of human dynamics. For example, some studies have utilized the call volume (Erlang value) or number of calls as indicators to monitor the spatiotemporal dynamics
of cities in real time (Liu et al. 2009, Calabrese et al. 2011), as well as for estimating the population distribution (Kang et al. 2012, Deville et al. 2014) and identifying the rhythms and variations in human dynamics for different cities or times (hourly, daily, weekly and monthly) (Sevtsuk and Ratti 2010, Ahas et al. 2015) using long-term data. In addition, visual analytics approaches have been proposed to analyze the spatiotemporal dynamics of human mobility (Sagl et al. 2012, Gao 2015). Recently, Yang et al. (2016) investigated human convergence and divergence patterns using mobile phone data. These three groups of approaches are very useful for understanding aggregate human mobility, but they are not capable of measuring the stability of aggregate human mobility (i.e. convergence or divergence).

In terms of stability measurement, the Shorrocks trace index is used to summarize mobility across cluster classes (Shorrocks 1978) and time (Hammond and Thompson 2002). Mitra et al. (2010) used this index to summarize the stability of the spatial patterns during school walking trips over time. Previously, it was stated that: ‘The Shorrocks index, however, does not yield complete information about mobility within the distribution’ and ‘does not differentiate between large and small movements within the distribution’ (Hammond and Thompson 2002, pp. 378). Entropy (Clausius 1850) was first introduced to measure reversible changes in thermal energy, which was extended to quantify the spatiotemporal stability of a link by Zayani et al. (2012). A high entropy value indicates a high level of disorder, whereas a low value indicates greater organization. However, entropy measurements only provide an overview of order quantification. In addition, the temporal stability of the structure of human mobility in urban space (Sun et al. 2011) has been investigated using principal component analysis. Very few studies have focused on the stability of human convergence and divergence. Therefore, for the first time, we propose an assessment model for measuring the stability of human convergence and divergence using mobile phone data.

3. Proposed assessment model

In this section, we introduce three definitions of aggregate human mobility: human convergence process (HCP), human divergence process (HDP) and daily human convergence and divergence sequence (HCDS). Next, we explain the model for assessing the stability of each human divergence or divergence process. Finally, we describe the overall assessment model for daily HCDSs based on the stability of divergence and divergence processes.

3.1. Definitions of human convergence and divergence

First, we introduce the concepts and definitions of human convergence and divergence. In the case of mobile phone data, all the locations of humans are recorded by cell phone towers. The outgoing flow (outflow) of a cell phone tower is defined as the cumulative movement number departing from the cell phone tower, whereas the incoming flow (inflow) of this tower is defined as the cumulative movements arriving at the cell phone tower. Figure 1 illustrates the outflow and inflow for cell phone tower A during time slot $T_i$. The netflow of the cell phone tower during this time slot $T_i$ is defined as:
A positive netflow indicates that the number of people served by the cell phone tower is increasing during the time slot, where we treat this status as convergence. By contrast, a negative netflow indicates that the number of people served by the cell phone tower is decreasing during the time slot, where we treat this status as divergence. The cumulative netflow of the cell phone tower in time slot $T_j$ can be calculated as:

$$N_j = \sum_{i=1}^{j} \text{netflow}_{T_i},$$  \hspace{1cm} (2)

where $N_j$ represents the cumulative netflow value for the cell phone tower in the time period from $T_1$ to $T_j$. Figure 2 shows the variation in the cumulative netflow for a cell phone tower over time slots during a day. It is obvious that this variation presents the human dynamics of the cell phone tower. For each tower, there is a time series of cumulative netflow variation (Figure 2), which represents its human dynamics. Based on
this representation, we introduce several definitions of human convergence and divergence, as follows.

**Definition 1** Time-dependent cumulative netflow sequence: Let \( N = \langle N_1, N_2, \ldots, N_j, \ldots, N_T \rangle \) be the time sequence of a cumulative netflow belonging to a cell phone tower, where \( N_j \) represents the cumulative netflow within time unit \( T_j \). A subsequence \( N' \) includes part of \( N \), which is represented as \( N' = \langle N_i, N_{i+1}, N_{i+2}, \ldots, N_j \rangle, 1 \leq i \leq j \leq T \), where \( T \) represents the total time slots in a day.

**Definition 2** HCP: If a subsequence of \( N \), i.e. \( N' = \langle N_i, N_{i+1}, N_{i+2}, \ldots, N_j \rangle \), meets the following conditions in Equation (3), which means that the cumulative netflow is increasing monotonically from \( T_i \) to \( T_j \), then it can be defined as a HCP. There are two exceptional cases: case 1 is \( i = 1 \), which can ignore the first condition in Equation (3); and case 2 is \( j = T \), where \( T \) is the maximum time slot in the assessment, which can ignore the third condition in Equation (3). For example, the subsequences between time slots \( T_6 \) and \( T_{10}, T_{12} \) and \( T_{15} \) in Figure 2 are HCPs.

\[
\begin{align*}
N_i & \leq N_{i-1} \\
N_i & \leq N_{i+1} \leq N_{i+2} \leq \cdots \leq N_j.
\end{align*}
\]  

**Definition 3** HDP: If a subsequence of \( N \), i.e. \( N' = \langle N_i, N_{i+1}, N_{i+2}, \ldots, N_j \rangle \), meets the following conditions in Equation (4), which means that the cumulative netflow is decreasing monotonically from \( T_i \) to \( T_j \), then the subsequence of \( N \) can be defined as a HDP, except for the two cases related to HCP in the definition above. For example, the subsequences between time slots \( T_1, T_6, T_{10} \) and \( T_{12} \), and \( T_{15} \) and \( T_{23} \) in Figure 2 are HDPs.

\[
\begin{align*}
N_i & \geq N_{i-1} \\
N_i & \geq N_{i+1} \geq N_{i+2} \geq \cdots \geq N_j.
\end{align*}
\]  

**Definition 4** HCDS: The variation in the cumulative netflow of a phone tower can be defined as a sequence of alternations between HCP and HDP. The HCDS is used to represent the human dynamics of this cell phone tower. For example, as shown in Figure 2, the changes in the cumulative netflow with yellow shading indicate the HCP, whereas those with blue shading indicate the HDP. The HCDS of this cell phone tower can be modeled as: HDP → HCP → HDP → HCP → HDP. We propose an assessment model for quantifying the stability of HCP, HDP and HCDS.

### 3.2. Stability of HCP or HDP

Before defining the stability of human convergence and divergence, we first consider their characteristic variations. Figure 3 shows four examples of HCPs. \( T_s \) and \( T_e \) represent the start and end time slot of each convergence process, and \( N_s \) and \( N_e \) represent the corresponding cumulative netflow at start time slot \( T_s \) and end time slot \( T_e \), respectively. We assume that these processes have the same \( N_s \) and we consider some different situations for this HCP, as
follows. (1) All four processes have the same value of $N_s$ but the duration of the convergence process in Figure 3(c) is longer than that of the other three processes. (2) The cumulative netflow $N_e$ at the end time slot is the same in Figure 3(b)–(d), but in Figure 3(a), $N_e$ is smaller than that in the other three processes. (3) Both the duration and cumulative netflow are the same in Figure 3(b,d), but the fluctuation of the HCP in Figure 3(b) is weaker than that in Figure 3(d). Therefore, these specific characteristics should be considered when quantifying the stability of the human dynamics of a place.

Due to the differences discussed above, we measure the stability by combining three factors, i.e. the duration ($T_e - T_s$), magnitude ($N_e - N_s$) and fluctuation (which indicates the extent of variation during a human convergence or divergence process). If two HCPs have the same magnitude ($N_e - N_s$), the HCP with a longer duration is considered to be more stable than the other HCP with a shorter time duration. If two HCPs have the same duration, the HCP with the smaller magnitude is considered to be more stable than the HCP with a larger magnitude. If two HCPs have the same duration and magnitude, the HCP with a smaller fluctuation is considered to be more stable than the other HCP with a greater fluctuation. Thus, the duration, magnitude and fluctuation are used to quantify differences when assessing the stability of HCPs.

The trend in the variation of the cumulative netflow ($N_e - N_s$) in a HCP is represented as a red dashed trend line in Figure 3, which indicates the intensity of human gathering during the time period between $T_e$ and $T_s$. The slope of the trend line can be used to quantify the intensity of the HCP:

$$v = \frac{N_e - N_s}{T_e - T_s}. \quad (5)$$

Figure 3. Examples of human convergence processes (HCPs). The red dashed line indicates the trend of human convergence and the black solid line indicates the variation in the cumulative netflow.
where \( v \) is the slope of the trend line, \( k \) is a scale parameter and the exponential function is employed to normalize \( v \), and thus the range of \( f \) is between zero and one. When \( f \) is near to 1, the HCP is constant during the time period, so the convergence process is very stable. When \( f \) is near to 0, the HCP undergoes extreme growth during the time period, so the HCP is highly unstable. In this manner, \( f \) can measure the stability of the HCP by integrating variations in the cumulative net flow and the duration.

To quantify the differences in the fluctuations of the HCPs in Figure 3(b,d), which have the same \( N_s \), \( N_e \) and time period, we calculate the values (plotted as blue nodes on the trend line) and summarize the difference between the trend values and real cumulative net flow values to denote the scope of the change in HCP. The trend line is formulated as follows:

\[
y = \frac{N_e - N_s}{T_e - T_s} \cdot (x - T_s) + N_s,
\]

Based on Equation (7), we calculate a trend value for each time slot \( T_i \). Therefore, each time slot has a different value (Equation 8) between the real cumulative net flow value \( N_i \) and the calculated trend value \( Y_i \). The standard deviation of these different values in a HCP is employed to quantify the fluctuation in the convergence process. If the HCP has smaller standard deviations (Equation 9) for these differences, then the fluctuation process is more stable. Similarly, an exponential function is employed to normalize the standard deviation using Equation (10):

\[
\Delta N_i = N_i - y_i,
\]

\[
\sigma_{\Delta N} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\Delta N_i - \Delta \bar{N})^2},
\]

\[
g = e^{-\frac{\Delta \bar{N}}{\Delta T}}, \quad \Delta T = T_e - T_s + 1,
\]

where \( \Delta \bar{N} \) represents the average value of \( \Delta N_i \) and \( \Delta T \) represents the duration of the convergence process. \( g \) ranges between zero and one, and the fluctuation in the HCP process is more stable when the value of \( g \) is larger.

After quantifying the stability of the trend line \( f \) and the fluctuation \( g \) for the HCP, we use Equation (11) to define the overall stability level of the HCP in a mutually independent manner:

\[
s = f \cdot g = e^{-k|v|} \cdot e^{-\frac{\Delta \bar{N}}{\Delta T}},
\]

where \( s \) represents the stability of the HCP process, which ranges between zero and one, and the HCP process is the more stable when the value of \( s \) is closer to one.

The stability of a HDP can be calculated in a similar manner to a HCP. The only difference in the process used for calculating a HCP and HDP is the slope of the trend lines. The slope of the trend line is positive in a HCP, whereas the slope is negative in a HDP. However, this is not important for assessing stability in the proposed model because we use the absolute value of the slope of the trend line.
3.3. Stability of daily convergence and divergence sequences

Based on the definitions of HCP and HDP, we propose a model for assessing the stability of the daily HCDSs for each cell phone tower. Figure 4 shows two examples of daily HCDSs. In the daily HCDS, the HCP is the rectangle filled with yellow lines and the HDP is that filled with blue lines. The stability of each HCP or HDP can be calculated using Equation (11), where \( s \) denotes the stability. Therefore, \( s_i \) and \( \Delta T_i \) in Figure 4 represent the stability value and duration time for the corresponding HCP or HDP, respectively. A HCP or HDP is more stable if the stability value \( (s_i) \) is larger or the duration \( (\Delta T_i) \) is longer, or both. Therefore, we use the area covered by these rectangles for HCP or HDP to indicate the relative changes in stability \( (A) \) for each HCDS, which is formulated as:

\[
A = \sum_{i=1}^{m} A_i = \sum_{i=1}^{m} s_i \cdot \Delta T_i, 
\]

\[
\sum_{i=1}^{m} \Delta T_i = T, 0 \leq A \leq T, 
\]

where \( m \) represents the total number of all processes, \( T \) is the total number of time slots and \( s_i \) ranges between zero and one, so the range of \( A \) is between zero and \( T \). In addition to the summed area of these processes, the fluctuation between HCP and HDP can also indicate the variation in the stability of the HCDS. For example, the two sequences in Figure 4 have the same area but the fluctuation in Figure 4(b) is more obvious than that in Figure 4(a), which indicates that the HCDS in Figure 4(b) is less stable than that in Figure 4(a). In order to distinguish this difference, we employ the

Figure 4. Examples of human convergence and divergence sequences. Area filled with blue lines is human divergent process, and area with orange lines is human convergent process. The red line is the boundary of convergence and divergence process.

---

The diagram shows two examples of HCDSs with different stability. The upper example (a) has a more stable pattern, with fewer fluctuations, while the lower example (b) shows more fluctuation, indicating less stability. The vertical axis represents the stability \( s \), and the horizontal axis represents the duration time \( T \). The area under each rectangle represents the change in stability over time.
length of the upper boundary (red line in Figure 4) to represent the fluctuation. A HCDS with a longer upper boundary has a greater fluctuation between a neighboring HCP and HDP; therefore, this HCDS is more unstable. The length can be calculated as follows:

\[
P = s_1 + \sum_{i=2}^{m} |s_i - s_{i-1}| + s_m + \sum_{i=1}^{m} \Delta T_i, \quad P \geq T. \tag{14}
\]

In order to combine the effects of the summed area and the length of the upper boundary on the stability of the HCDS, we assess the stability of the HCDS by using the ratio between them, as follows:

\[
Q = \frac{A}{P} = \frac{\sum_{i=1}^{m} s_i \cdot \Delta T_i}{s_1 + \sum_{i=2}^{m} |s_i - s_{i-1}| + s_m + \sum_{i=1}^{m} \Delta T_i}, \quad 0 \leq Q \leq 1, \tag{15}
\]

where \( A \) is less than or equal to \( P \), so the stability \( Q \) lies between zero and one. Equation (15) shows that if a HCDS has a larger stability value and a shorter upper boundary, then it will be more stable.

4. Experiment and results

4.1. Data set and preprocessing

The mobile phone location data set used in this study was collected by a major telecom operator in Shenzhen, which is a city with the highest population density and the fourth highest economic output in China. A recent census showed that Shenzhen City covers a total area of approximately 2000 km\(^2\), and it has a population of more than 15 million residents (Shenzhen Statistical YearBook 2012).

The mobile phone data set used in this study was acquired through a research collaboration. The data set comprised one workday of records for approximately 16 million cell phones. In contrast to call detail records that passively capture individual footprints only during actual communication such as phone calls and text messages (Yin et al. 2015, Zhao et al. 2016), the data set used in this study represents individual locations (at the cell phone tower level) approximately once every hour. Each record comprised an anonymous user ID, recording time, and the longitude and latitude of the cell phone tower used. Table 1 shows an example of a cell phone user’s records from one day. The time of each record was at a fine scale of seconds. In total, 5940 cell phone towers were extracted from the data set and each tower was labeled with a unique Tower-ID number (see Figure 5 in

<table>
<thead>
<tr>
<th>User ID</th>
<th>Record time</th>
<th>Time window</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>bfa8m7****</td>
<td>00:25:36</td>
<td>00:00–01:00</td>
<td>113.***</td>
<td>22.***</td>
</tr>
<tr>
<td>bfa8m7****</td>
<td>01:26:40</td>
<td>01:00–02:00</td>
<td>113.***</td>
<td>22.***</td>
</tr>
<tr>
<td>bfa8m7****</td>
<td>02:20:33</td>
<td>02:00–03:00</td>
<td>113.***</td>
<td>22.***</td>
</tr>
<tr>
<td>bfa8m7****</td>
<td>23:33:50</td>
<td>23:00–24:00</td>
<td>113.***</td>
<td>22.***</td>
</tr>
</tbody>
</table>
which, for privacy protection, individual records have been smoothed using a spatial kernel density surface generated based on the locations of the cell phone towers).

For each cell phone, the space–time trajectory can be constructed as follows:

\[
Tr = [p_1(x_1, y_1, t_1, ld_1), p_2(x_2, y_2, t_2, ld_2), \ldots, p_n(x_n, y_n, t_n, ld_n)],
\]

where \(x_i, y_i\) and \(ld_i\) are the longitude, latitude and Tower-ID of recording point \(p_i\), and \(t_i\) represents the time when the location of the cell phone was updated. Each record was allocated to a time window of approximately 1 hour (Table 1). For every pair of adjacent time windows, if the locations of the two recording points were not identical (\(x_i \neq x_{i+1}\) or \(y_i \neq y_{i+1}\)), then this indicated that a movement occurred between the two time windows. We recorded the original and terminal Tower-ID of the movement and identified the two adjacent time windows as a time slot. For example, \(p_1\) was recorded by cell phone tower \(ld_i\) during time window 00:00–01:00 and \(p_2\) was recorded by cell phone tower \(ld_j\) during the next time window 01:00–02:00. If \(ld_i \neq ld_j\), then a movement could be extracted from \(ld_i\) to \(ld_j\), and the two adjacent time windows 00:00–02:00 could be denoted as the time slot \(T_1\). In this manner, we extracted all the movements for time slots \(T_1\) (00:00–02:00), \(T_2\) (01:00–03:00), \(T_3\) (02:00–04:00), \ldots, \(T_23\) (22:00–24:00). Thus, there were 23 time slots in one day. For each time slot, we used all the extracted movements to create inflow, outflow and netflow data for the cell phone tower at each time slot, which we used to measure the stability of human convergence and divergence.

4.2. Stability of HCP or HDP

We extracted 22,234 HCPs and 21,132 HDPs from the data set and calculated the stability of these HCPs and HDPs for each cell phone tower according to Equation (11). The selection of the scale parameter \(k\) in Equation (6) depends on the netflow values. In this data set, more than 95% of the netflow values varied between −1000 and 1000. If \(k = 1\), the value of \(f\) is extremely small, so we used \(k = 0.01\) to ensure that \(k^*|v|\) was between −10 and 10 because the value of \(f\) could be normalized in a range of [0, 1]. Figure 6 shows the distribution of the stability for the HCPs and HDPs. More than 42% of the HCPs and 37.6%
of the HDPs were greater than 0.75 for these cell phone towers. In order to determine the similarity between the percentages in Figure 6(a,b), we used Pearson’s correlation coefficient $R$ (Pearson 1920), which is defined as:

$$ R = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \cdot \sum_{i=1}^{n} (y_i - \bar{y})^2}} $$

(17)

where $x_i$ and $y_i$ are the different stability percentages, and $\bar{x}$ and $\bar{y}$ are the average percentages. The $R$ value calculated between the percentages in Figure 6(a,b) is 0.944, and thus the percentage distribution for HCP and HDP was relatively close. This indicates the symmetry of urban human flow, i.e. the inflow for a cell phone tower always comes from the outflow of another cell phone tower. Hence, the results obtained in this study are consistent with expectations.

To investigate the differences in stability for the HCPs and HDPs in different time periods during the day, we selected three time periods: morning (06:00–12:00), afternoon (12:00–17:00) and evening (17:00–23:00). Figure 7 shows the stability distributions for the HCPs and HDPs in the morning, afternoon and evening, where their Pearson’s $R$ values are 0.989, 0.620 and 0.925, respectively, which means that the HCPs and HDPs had similar percentage variation patterns, especially in the morning and evening.

Some specific stability distribution patterns are shown in Figure 7. For example, the percentages of both unstable HCPs and HDPs in the morning were the highest among the three periods, followed by the evening. The stability percentage distribution was more homogeneous in the afternoon than the other two time periods. The relatively high HCP and HDP percentages in the morning and evening represent the high intensity of human mobility associated with the commuting period, which was more unstable than that in the afternoon.

### 4.3. Assessing the HCDS stability for people covered by TAZs

Based on the assessments of HCPs and HDPs for cell phone towers, we employed the proposed approach to assess the HCDS stability for people covered by urban TAZs. TAZs
are the primary spatial units used in analyses, where trips begin and end in transportation planning, and they play important roles in travel demand forecasting models (e.g. trip generation and trip distribution) (You et al. 1998, Dong et al. 2015). Assessing the stability of TAZs is helpful for understanding the aggregate human mobility in these zones, and it can support the division of TAZs during transportation planning.

To assess the stability of HCDS, we aggregated the inflow, outflow and netflow derived from the space–time trajectories of mobile phones and calculated the stability in each TAZ using the proposed method. Figure 8 shows the statistical distribution of stability for individual TAZs, which demonstrates that over 85% of the TAZs had stability values smaller than 0.5. Figure 9 shows the spatial distribution of stability, where there are several obvious patterns. First, most of the TAZs with the highest stability were located in the eastern part of the city, as shown by the red color in Figure 9. These areas included green industrial zones and nature preservation zones. Second, the HCDS was more unstable in the southern part of the city because this is the economic center of the city, which includes most of the companies, residential areas, shopping malls,
restaurants, financial institutions and recreational venues (bars, cinemas, etc.). These locations usually attract numerous people to work, shop, eat, visit entertainment centers and engage in other activities during the daytime. In addition, the HCDS was very unstable at three major traffic hubs (airport, Shenzhen railway station and Shenzhen north railway station) and some highway intersections. These locations are very important for connecting with areas outside the city, which suggests that the human convergence and divergence at these locations changed greatly during the daytime. According to the spatial patterns shown in Figure 9, the stability value at individual cell phone towers can be used to support the subdivision of TAZs. Previously, Dong et al. (2015) extracted four characteristics of human mobility (i.e. real-time user volume, inflow, outflow and incremental flow) from mobile phone data to obtain TAZ subdivisions. Based on these data, transportation planners can introduce separate policies for stable and unstable TAZs in order to make transportation systems more efficient.

4.4. Assessing the HCDS stability for people covered by a bus transit system

We also used the proposed assessment model to evaluate the HCDS stability of people covered by a bus transit system, which could help to understand the potential demand for a bus transit system and facilitate policy decisions, such as adjusting the bus timetable or routes according to the number of people served.

We used mobile phone data to assess the stability of the people who were most likely served by each bus stop. According to the design criteria for public transport stops (National Standards of China, GB50220-95, 1995) and the distance people normally walk to access a bus stop (Delbosc and Currie 2011), we selected 500 m as the area covered by a bus stop. Due to the limitation of the mobile phone data set, it was impossible to know the exact bus stops to which people walked and the people served by each bus stop. Therefore, for each bus stop, we could only use the cell phone towers located within 500 m to assess the stability of the bus stop. It was possible that some towers were covered by two or more bus stops, which could lead to some estimation errors, but

![Figure 9. Spatial distribution of stability for traffic analysis zones.](image-url)
the results of this analysis are still useful for understanding human convergence and divergence in a bus transit system at the aggregate level.

We used a distance of 500 m to search for mobile phone towers near a bus stop (Figure 10), and we assumed that the people near each tower could be covered by the bus stop. The *netflow* of each bus stop was calculated by aggregating the *inflow*, *outflow* and *netflow* derived from the space–time trajectories of the mobile phones that entered or left the area within 500 m of the bus stop. We then calculated the stability of each bus stop in the same manner as the cell phone towers.

Figure 11 shows the stability of all the bus stops during one day. To understand the HCDS stability, we grouped the stability values of all the bus stops into five levels with an interval of 0.2. In Figure 11, groups A and E represent the lowest and highest levels of stability, respectively. Most of the bus stops with the lowest stability were located in large industrial zones (i.e. a, b, c and f), high-tech parks (i.e. d and g) and urban central business districts (i.e. h and j).

A bus line comprised bus line segments according to the representation of a bus line system in the GIS for transportation. The HCDS stability of a bus line segment between two bus stops was set as the average HCDS stability value for these bus stops. Based on the assigned HCDS stability values, we also grouped the stability values into five levels in the same manner as the bus stops. Figure 12 illustrates the HCDS stability results obtained for all the bus lines, which shows that 62.4% of the bus line segments had stability level C, and thus most of the bus line segments had a relatively stable human convergence and divergence status. Very few bus line segments had the highest level of

![Figure 10. Area covered by bus stops.](image1)

![Figure 11. Human convergence and divergence sequence (HCDS) stability for urban bus stops.](image2)
stability, and they were located in the relatively rural part of this study area (i.e. the green lines in Figure 12). The highly unstable areas of the bus line segments were located in the center of the city (i.e. g, h and i) and close to Shenzhen airport (i.e. a).

According to the rhythm of daily life for urban citizens, we divided the whole day into seven time periods (see Table 2), which included the main meaningful activity periods within a day. These seven time periods were used to examine the detailed HCDS stability for bus lines, which could help bus companies to understand the adjustments needed to their routine timetable and routes in order to meet the requirements of bus users.

Tables 3 and 4 show the percentages of bus stops and the service distances of the bus line segments in five levels for the seven time periods, which demonstrate that 75.2% of the bus stops and 84.4% of the service distances of the bus line segments were located at level E in $T_1$, because most people were sleeping at home during this time period. In addition, 19.3% and 45.5% of bus stops were at levels A and B, respectively, during the morning commuting period $T_2$, which were higher than those in the evening commuting period $T_6$ (5.8% at level A and 26.8% at level B). The HCDS stability of the bus line segments also exhibited similar patterns.

![Figure 12. Human convergence and divergence sequence (HCDS) stability for bus line segments.](image)

**Table 2.** The seven time periods used in this study.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Main activity</th>
<th>Time period</th>
<th>Main activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>00:00–06:00 Sleep time</td>
<td>$T_3$</td>
<td>14:00–17:00 Afternoon work time</td>
</tr>
<tr>
<td>$T_2$</td>
<td>06:00–09:00 Morning commute time</td>
<td>$T_6$</td>
<td>17:00–20:00 Evening commute time</td>
</tr>
<tr>
<td>$T_3$</td>
<td>09:00–12:00 Morning work time</td>
<td>$T_7$</td>
<td>20:00–24:00 Free time</td>
</tr>
<tr>
<td>$T_4$</td>
<td>12:00–14:00 Lunch time</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.** Percentage of bus stops at the five levels for the seven time periods.

<table>
<thead>
<tr>
<th>Time period</th>
<th>A (%)</th>
<th>B (%)</th>
<th>C (%)</th>
<th>D (%)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>0.1</td>
<td>0.3</td>
<td>2.0</td>
<td>22.4</td>
<td>75.2</td>
</tr>
<tr>
<td>$T_2$</td>
<td>19.3</td>
<td>45.5</td>
<td>28.6</td>
<td>5.2</td>
<td>1.4</td>
</tr>
<tr>
<td>$T_3$</td>
<td>5.1</td>
<td>23.1</td>
<td>41.4</td>
<td>26.4</td>
<td>4.0</td>
</tr>
<tr>
<td>$T_4$</td>
<td>4.6</td>
<td>16.3</td>
<td>39.2</td>
<td>32.7</td>
<td>7.2</td>
</tr>
<tr>
<td>$T_5$</td>
<td>3.6</td>
<td>19.3</td>
<td>47.1</td>
<td>25.8</td>
<td>4.2</td>
</tr>
<tr>
<td>$T_6$</td>
<td>5.8</td>
<td>26.8</td>
<td>41.7</td>
<td>22.1</td>
<td>3.6</td>
</tr>
<tr>
<td>$T_7$</td>
<td>3.1</td>
<td>17.3</td>
<td>39.2</td>
<td>32.4</td>
<td>8.0</td>
</tr>
</tbody>
</table>
These results indicate that human mobility is more unstable in the morning commuting period than the evening commuting period, which suggests that bus companies need to pay more attention to the travel demands in these unstable areas (e.g. the lines at level B) by monitoring flows and responding to unstable flows with different strategies in terms of the bus line departure interval. Thus, they can improve the performance of bus line services by saving energy and making full use of labor resources. By contrast, in time

### Table 4. Percentage of service distances of the bus line segments at the five levels for the seven time periods.

<table>
<thead>
<tr>
<th></th>
<th>A (%)</th>
<th>B (%)</th>
<th>C (%)</th>
<th>D (%)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_1</td>
<td>0.4</td>
<td>0.7</td>
<td>1.7</td>
<td>12.8</td>
<td>84.4</td>
</tr>
<tr>
<td>T_2</td>
<td>5.0</td>
<td>42.9</td>
<td>44.3</td>
<td>6.9</td>
<td>0.9</td>
</tr>
<tr>
<td>T_3</td>
<td>0.7</td>
<td>9.9</td>
<td>40.3</td>
<td>44.9</td>
<td>4.2</td>
</tr>
<tr>
<td>T_4</td>
<td>0.8</td>
<td>5.2</td>
<td>35.6</td>
<td>49.5</td>
<td>8.9</td>
</tr>
<tr>
<td>T_5</td>
<td>0.7</td>
<td>6.6</td>
<td>48.8</td>
<td>40.7</td>
<td>3.2</td>
</tr>
<tr>
<td>T_6</td>
<td>1.6</td>
<td>19.5</td>
<td>48.1</td>
<td>28.4</td>
<td>2.4</td>
</tr>
<tr>
<td>T_7</td>
<td>0.7</td>
<td>8.8</td>
<td>37.3</td>
<td>45.0</td>
<td>8.2</td>
</tr>
</tbody>
</table>

(see Figure 13). These results indicate that human mobility is more unstable in the morning commuting period than the evening commuting period, which suggests that bus companies need to pay more attention to the travel demands in these unstable areas (e.g. the lines at level B) by monitoring flows and responding to unstable flows with different strategies in terms of the bus line departure interval. Thus, they can improve the performance of bus line services by saving energy and making full use of labor resources. By contrast, in time

#### Figure 13. Human convergence and divergence sequence (HCDS) stability of bus line segments in $T_2$ and $T_6$. 

*Downloaded by [University Town Library of Shenzhen] at 00:26 05 September 2017*
periods $T_3$, $T_4$, $T_5$ and $T_7$, most of the bus stops and bus line segments were at levels C and D, which indicates that human convergence and divergence were relatively stable during these time periods. These patterns suggest that the bus line departure intervals in these time periods do not need to be adjusted dynamically, but instead the departure intervals should be decided by the actual travel flows in these areas.

5. Discussion

In order to assess the suitability of the proposed model in identifying spatiotemporal stability of aggregate human convergence and divergence patterns, we compare the results of the proposed model with the entropy measure. Entropy is a widely used index for examining the stability of a system, and it has been employed recently to reflect the heterogeneity of human movements (Song et al. 2010). In this study, we compared the difference in performance between entropy and the proposed assessment model for determining the stability of daily human dynamics in a place.

Based on the defined time series of the cumulative netflow for a cell phone tower (see Figure 2), the entropy of human dynamics for a cell phone tower can be calculated as follows:

$$\text{sum}_N = \sum_{i=1}^{23} |N_i|, \quad (18)$$

$$p_i = \frac{|N_i|}{\text{sum}_N}, \quad (19)$$

$$E = - \sum_{i=1}^{23} p_i \cdot \log_2 p_i, \quad (20)$$

where $E$ represents the entropy index. A larger entropy value for a cell phone tower indicates that each netflow $N_i$ is close to the average value of sum$_N$, which indicates that the time series of the cumulative netflow for a tower is more stable.

Figure 14 illustrates the distribution of the entropy value and the proposed stability model, where this figure shows that they do not have a linear relationship, which indicates that the entropy and proposed stability model differ in their ability to reflect the HCDS stability.

In order to compare the differences between entropy and the proposed stability model, we selected cell phone towers with comparable entropy values and stability values, and then visualized the time series for the cumulative netflow to check the human dynamics around these cell phone towers. It should be noted that no specific rule was employed for selecting the entropy or stability values. Figure 15(a) shows the time-dependent cumulative netflow for the entropy values at 3.9, 4.0 and 4.1. Figure 15(b) shows the time-dependent cumulative netflow for the stability values at 0.5, 0.6 and 0.7. An obvious pattern is visible in Figure 15(a) where the cumulative netflow varies significantly whereas the entropy value remains the same. However, the proposed model can reflect the stability of the cumulative netflow better than the entropy value because the time series of the cumulative netflow with a high stability value derived from...
the proposed model does not exhibit large variations (e.g. levels D and E in Figure 15(a)), whereas those with a low value have larger variations (e.g. level A in Figure 15(a)). This result indicates that entropy performed poorly at reflecting the variations in the time series of the cumulative netflow between different towers. Figure 15(b) shows the capacity of the proposed model for measuring variations in the time series of the cumulative netflow, but these lines also exhibit some variations with different entropy values. Therefore, Figure 15 demonstrates that entropy is a better option for comparing variations in the aggregate human mobility for an individual cell phone tower during different time periods, whereas the proposed stability model is better for comparing the differences in aggregate human mobility between different cell phone towers. To some extent, these two indicators are complementary to each other and they can be used together to assess the stability of aggregate human mobility.

6. Conclusion

In this study, we proposed a model for assessing the stability of the daily HCDS, which we used to assess the HCDS stability for a cell phone tower, TAZs and bus lines. The experimental results obtained in this study demonstrate the capacity of the proposed model for finding potentially unstable areas of human mobility. These areas can then be used to facilitate decision-making, such as time-varying bandwidth assignment for a mobile communication system based on the HCDS stability of cell phone tower, combining or separating TAZs according to the HCDS stability of TAZs, responding to unstable flows with different strategies for bus line departure intervals and helping to find a suitable departure interval according to the HCDS stability of bus stops and bus lines. In addition, we compared the capacity of entropy and the proposed model for representing HCDS, and
we concluded that entropy can compare the variations for a tower in different time period series, whereas the proposed stability model can compare the variations for different towers. Both measures can be used in a complementary manner.

The proposed model is capable of assessing the stability of human convergence and divergence with different spatial units (e.g. cell phone towers, bus lines and TAZs). Thus, the model can be applied to other cities or data sets to inform decision-making during transport planning. The results of this study are based on mobile phone data that included most of the population of a city. Therefore, our results reflect certain aspects of the aggregate characteristics of human convergence and divergence. In the future, it would be useful to apply the same model to other types of data sets, such as transit smart card data and floating car data, in order to capture a more comprehensive overview of the human convergence and divergence patterns in a city. In addition, there is a common problem when the signal switches between adjacent cell phone towers.

Figure 15. Variations in the cumulative netflow for cell phone towers with the same: (a) entropy = 3.9, 4.0 and 4.1; or (b) stability = 0.5, 0.6 and 0.7.
towers. We focused on aggregate population flows rather than individual mobility patterns, but we consider that our results are not highly sensitive to this issue because signal switches tend to balance out with each other at an aggregate level. However, this is a data issue that researchers should consider when conducting mobility research using mobile phone data.

In future research, we may need to integrate mobile phone location data with other data sources, such as CCTV video monitoring data, smart transit card data from a city or social media data to obtain more accurate flow assessments. In addition, our future research may focus on investigating the relationships between the HCDS stability and the spatial and social characteristics of urban systems, such as land-use functions and points of interest.

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